REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
12-06-2012	Conference Proceeding	-

4. TITLE AND SUBTITLE
Acoustic travel-time tomography of the atmosphere at the Boulder Atmospheric Observatory

5a. CONTRACT NUMBER
W911NF-10-1-0415

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611102

6. AUTHORS
Vladimir Ostashev, Sergey Vecherin, Keith Wilson, Alfred Bedard, Jesse Leach, Kurt Clark, Christofer Fairall, Daniel Wolfe

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
University of Colorado - Boulder
The Regents of the University of Colorado
Office of Contracts and Grants
Boulder, CO 80309 -0572

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
57813-EV.4

12. DISTRIBUTION AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
see Abstract in the paper

15. SUBJECT TERMS
acoustic tomography, temperature and velocity fields

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UU	UU	UU	UU		Vladimir Ostashev
					19b. TELEPHONE NUMBER
					303-497-3712

Report Title

Acoustic travel-time tomography of the atmosphere at the Boulder Atmospheric Observatory

ABSTRACT

see Abstract in the paper

Conference Name: 16th International Symposium for the Advancement of the Boundary-Layer Remote Sensing

Conference Date: June 05, 2012

Extended Abstracts of Presentations from the

16th International Symposium for the Advancement of Boundary-Layer Remote Sensing

5-8 June 2012
Boulder, Colorado

ISARS 2012

ISARS 2012

Extended Abstracts of Presentations from the

16th International Symposium for the Advancement of Boundary-Layer Remote Sensing

5-8 June 2012
Boulder, Colorado

Extended Abstracts of Presentations from the 16th International Symposium for the Advancement of Boundary-Layer Remote Sensing, 5-8 June 2012, Boulder, CO USA

Printed in the United States

Cover Photo: Mt. Audubon *(right)* at Brainard Lake, Colorado, © 2011 Paul Neiman

ACOUSTIC TRAVEL-TIME TOMOGRAPHY OF THE ATMOSPHERE AT THE BOULDER ATMOSPHERIC OBSERVATORY

V. E. Ostashev[1,2], S. N. Vecherin[2], D. K. Wilson[2], A. J. Bedard[1], J. L. Leach[3], K. A. Clark[3], C. W. Fairall[3], and D. E. Wolfe[1]

[1]*CIRES/University of Colorado at Boulder and NOAA/Earth System Research Laboratory, 325 Broadway, Boulder, CO, 80305, USA, vladimir.ostashev@noaa.gov*
[2]*U.S. Army Engineer Research and Development Center, 72 Lyme Road, Hanover, NH, 03755, USA*
[3] *NOAA/Earth System Research Laboratory, 325 Broadway, Boulder, CO, 80305, USA*

ABSTRACT

Acoustic tomography of the atmospheric surface layer (ASL) is based on measurements of travel times of sound propagation between speakers and microphones, which constitute a tomography array. The temperature and wind velocity fields inside the tomographic region affect the travel times and can be reconstructed using different inverse algorithms. An array for acoustic tomography of the ASL has recently been built at the Boulder Atmospheric Observatory (BAO), CO, USA. The array consists of three speaker and five microphone towers located along the perimeter of a square with side length of 80 m. Speakers and microphones are connected via underground cables to the central command and data acquisition computer and other equipment located in a small modular building at the BAO. Using the BAO tomography array, the travel times of sound impulses between the speakers and microphones have been measured and analyzed. Subsequent reconstruction of the temperature and wind velocity fields is done with a recently developed time-dependent stochastic inversion. Examples of the reconstructed turbulence fields are presented and analyzed. Other developments in acoustic tomography are briefly discussed.

1. INTRODUCTION

Acoustic travel-time tomography of the atmospheric surface layer (ASL) is based on measurements of travel times of sound propagation between acoustic sources (usually, speakers) and microphones. Then, the temperature and wind velocity fields inside the tomographic region (area or volume) are reconstructed using different inverse algorithms. Improved knowledge about these fields is important for boundary layer meteorology, theories of turbulence, studies of sound and electromagnetic wave propagation in a turbulent atmosphere, etc. Acoustic tomography of the ASL has certain advantages [1] in comparison with point measurements of temperature and wind velocity using conventional meteorological devises.

The first experimental implementation of acoustic tomography of the ASL was done by Wilson and Thomson [2]. Since the mid 1990's, many outdoor and indoor acoustic tomography experiments have been performed by scientists from the University of Leipzig, Germany, e.g., see [3,4]. At the end of the 2010's, an array for acoustic tomography of the ASL was built [1,5] at the Boulder Atmospheric Observatory (BAO), near Boulder, CO, USA. The BAO is a premier meteorological site with many instrumentation for measurements of parameters of the atmospheric boundary layer.

In Sec. 2, the layout and principle of operation of the BAO acoustic tomography array are briefly discussed. A recently developed time-dependent stochastic inversion (TDSI) algorithm for reconstruction of the temperature and wind velocity fields from the travel times of sound propagation is outlined in Sec. 3. In Sec. 4, examples of the temperature and velocity fields reconstructed with the BAO array and TDSI algorithm are presented and discussed. In Sec. 5, other recent developments in acoustic tomography are outlined. In Sec. 6, the results obtained in the paper are summarized.

2. BAO ACOUSTIC TOMOGRAPHY ARRAY

The BAO acoustic tomography array consists of three speaker and five microphone towers located along the perimeter of a square with side length of 80 m. The towers are 9.1 m high; their (x, y) coordinates in a horizontal plane are shown in Fig. 1. Speakers and microphones are located on the towers at three adjustable levels ranging from about 3 to 9 m. Transducers at the upper level of the towers have been used so far for transmission and reception of acoustic signals, thus enabling 2D, horizontal slice tomography. Speakers and microphones are connected via underground cables to equipment inside a small modular building at the BAO: microphone filters, powers amplifiers, A/D interfaces, a central control and data acquisition computer, and an uninterruptible power supply.

Software was developed to run acoustic tomography experiments from the central computer and to store all

data on the computer. The software allows choosing the form of a transmitted signal (with a length of about 30 ms) and the duration of an experiment (from 1 min to a few hours). In the current design, three speakers are activated in a sequence with 0.5 s delay. Five microphones record these signals. The travel times τ_i of sound propagation along different sound propagation paths are determined by the cross-correlation of the transmitted and received signals. Here, the subscript $i = 1,2,\ldots,15$ indicates a particular path shown in Fig.1. The temperature $T(x,y,t)$ and wind velocity $\vec{v}(x,y,t)$ fields inside the BAO tomography array are reconstructed from the measured travel times τ_i using the TDSI algorithm (explained in the next section). Here, t is time.

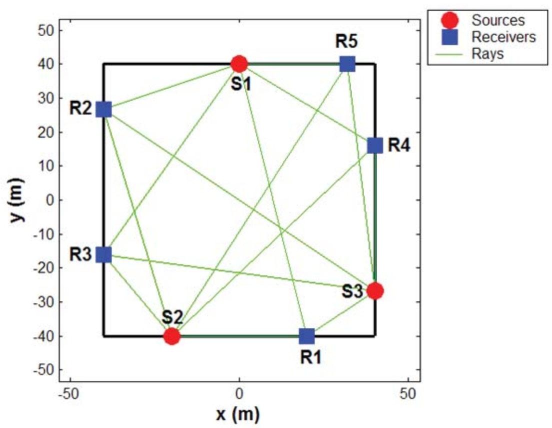

Figure 1. Location of eight towers of the BAO acoustic tomography array in a horizontal plane. Green lines indicate sound propagation paths from speakers (red circles) to microphones (blue squares).

To the best of our knowledge, the BAO tomography array is currently the only operational array for acoustic tomography of the ASL. The speakers and microphones are permanently installed on the towers. This allows continuous monitoring of the temperature and wind velocity fields. All previous tomography arrays were dismantled after a short time of operation.

Efforts are underway to upgrade capabilities of the BAO tomography array. Two new towers have been already mounted and connected via underground cables with the BAO modular building. All towers, except one in the middle of the array, will have both a speaker and microphone installed at the upper level of the array that will increase the number of sound propagation paths and allow reciprocal transmission. A sonic anemometer and thermometer probe will be installed on the tower, which is located in the middle of the array. A new PC and better A/D interfaces will be used to improve synchronization in transmitting and recording of acoustic signals, and to make more accurate measurements of the travel times.

3. TDSI ALGORITHM

In the TDSI algorithm, the temperature and wind velocity fields are expressed as sums of the mean fields and the fluctuations: $T(x,y,t) = T_0(t) + T_1(x,y,t)$, $\vec{v}(x,y,t) = \vec{v}_0(t) + \vec{v}_1(x,y,t)$. Here, the subscripts "0" and "1" correspond to the mean fields and the fluctuations, respectively. The mean fields are reconstructed with the least squares solution and the fluctuations with the TDSI algorithm.

The main idea of TDSI is to measure the travel times τ_i repeatedly at the time moments t_1, t_2, …, t_n, where n is the number of travel time measurements, and to assume that the temperature and velocity fluctuations are random fields with known spatial-temporal correlation functions. Using n sets of the travel times τ_i as input data, the $T_1(x,y,t)$ and $\vec{v}_1(x,y,t)$ fields are reconstructed with approaches developed in [6-9]. By repeated measurements of the travel times, TDSI increases the number of data used in the inversion without increasing the number of speakers and microphones, i.e., the number of sound propagation paths. Numerical results showed that TDSI allows better reconstruction of the temperature and velocity fields than other algorithms do, for example, stochastic inversion.

The developed TDSI was applied to numerical simulations of the BAO acoustic tomography array. In the simulations, the temperature and velocity fields were modeled with large eddy simulations (LES). The results obtained showed that the mean temperature and wind velocity and their fluctuations can be reliably reconstructed. The developed TDSI was also applied for reconstruction of the temperature and velocity fields in outdoor [3] and indoor [4] acoustic tomography experiments carried out by scientists from the University of Leipzig. The results obtained showed successful reconstruction of the temperature and wind velocity fields, which were in a good agreement with in situ measured data where those were available.

4. RECOSNTRUCTION OF TEMPERATURE AND VELOCITY FIELDS

After a thorough testing and refinement, the TDSI algorithm was applied for reconstruction of the temperature and wind velocity fields in acoustic tomography experiments with the BAO tomography array. The results presented below [9] correspond to the tomography experiment, carried out on 09 Jul 2008 at 21:31-21:33 UTC (15:31-15:33 of local time).

Figure 2 depicts the temporal evolution of the travel time $\tau_1(t)$ of signal propagation from speaker 1 to microphone 1 shown in Fig. 1. The travel time was calculated every 1.5 s during 180 s of the tomography experiment. The travel time gradually changes from one measurement to another due to changing temperature and wind velocity fields. A maximum deviation of the travel time from its mean value is of the order of 0.5 ms. Though not shown here for brevity, the travel times along other propagation paths depicted in Fig. 1 exhibit a similar temporal evolution.

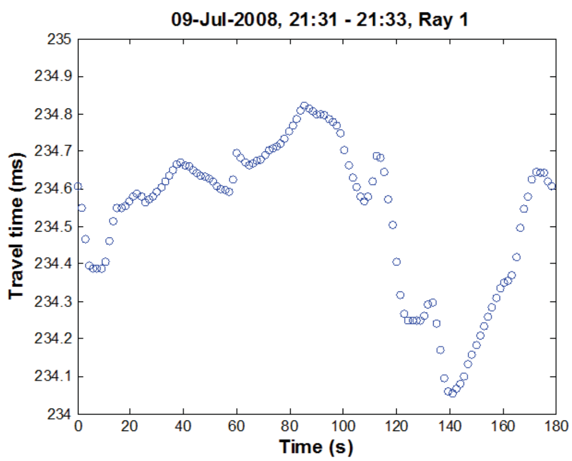

Figure 2. Temporal evolution of the travel time of sound propagation from speaker 1 to microphone 1 shown in Fig. 1 in the acoustic tomography experiment at the BAO on 09 Jul 2008.

The measured travel times τ_i were then used to reconstruct the temperature and wind velocity fields. Figure 3 shows the reconstructed temperature field $T(x,y)$, which corresponds to the time 21:32:30 of the experiment. The expected error in reconstruction is about 0.05°. Several "cold" and "warm" eddies are clearly seen in the figure. The eddies are reliably resolved since the temperature difference between them is larger than the error in reconstruction.

The magnitude of the wind velocity vector reconstructed for the same time 21:32:30 is depicted in Fig. 4. The expected error of reconstruction is 0.04 m/s. "Fast" and "slow" eddies are seen in the figure. Arrows indicate the direction of the wind velocity vector.

Similarly, the temperature $T(x,y)$ and wind velocity $\vec{v}(x,y)$ fields were reconstructed for other time moments of the tomography experiments. The resulting spatial fields were combined into two "movies", which show temporal evolutions of the temperature and velocity fields for 180 s of the experiment.

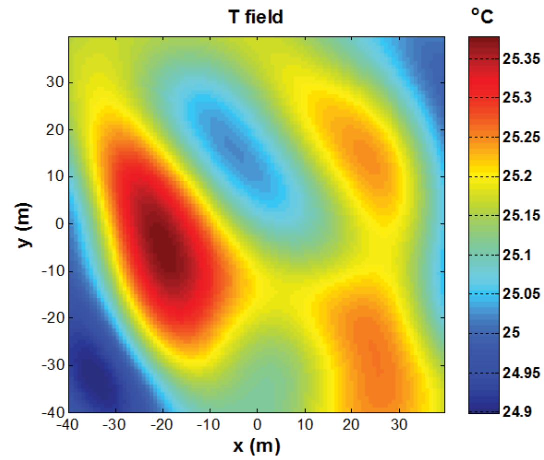

Figure 3. Temperature field reconstructed with TDSI in the acoustic tomography experiment at the BAO on 09 Jul 2008. (In color in the electronic version.)

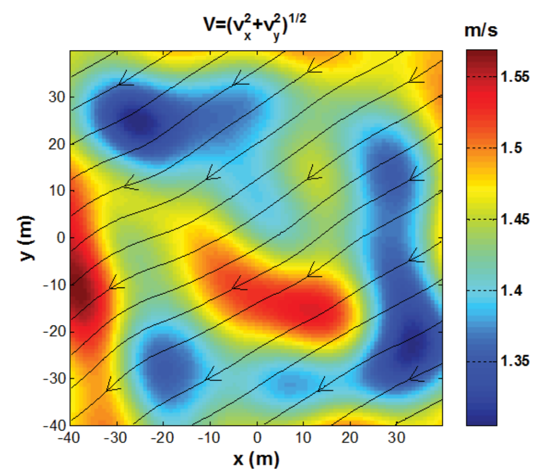

Figure 4. Magnitude of the wind velocity reconstructed with TDSI in the acoustic tomography experiment at the BAO on 09 Jul 2008. Arrows indicate the direction of the wind velocity vector. (In color in the electronic version.)

5. OTHER DEVELOPMENTS IN ACOUSTIC TOMOGARPHY

Though the BAO acoustic tomography array and the TDSI algorithm were built and developed to obtain results similar to those shown in Figs. 2-4, they can also be used for other research problems. In this section, we briefly outline some of these problems.

The BAO tomography array could be used a large sonic anemometer/thermometer for obtaining the area-averaged measurements of the temperature, wind velocity, and horizontal heat flux. Area-averaged measurements of these meteorological parameters are important since point measurements are often not representative due to spatial variations. An approach has been suggested to infer the vertical heat flux from

the horizontal heat flux. Preliminary theoretical and experimental results obtained in this study are reported in [10,11].

The BAO tomography array can be used for testing theories of line-of-sight sound propagation through a turbulent atmosphere, including theories of broad-band propagation and temporal coherence, which are yet to be developed. In such experiments, the tomography array could provide information about both atmospheric turbulence and fluctuations in acoustic signals propagating through the turbulence.

Finally, to improve a spatial resolution of a sonic anemometer/thermometer, one might regard it as a small acoustic tomography array [10], and use the TDSI algorithm for fine reconstruction of the temperature and wind velocity fields. Numerical simulations have shown that if the number of transducers in a sonic is doubled, its spatial resolution would increase by a factor of ten.

6. CONCLUSIONS

In this paper, the layout and principle of operation of the BAO acoustic tomography array were presented. The array enables measurement of the travel times of sound signal propagation between different speakers and microphones, which constitute the tomography array. Efforts underway to upgrade capabilities of the BAO tomography array were outlined. The TDSI algorithm, which is used for reconstruction of the temperature and wind velocity fields from the measured travel times, was briefly explained and the results obtained with this algorithm were overviewed. The results in reconstruction of the temperature and wind velocity fields in the acoustic tomography experiment at the BAO on 09 Jul 2008 were presented and analyzed. The use of the BAO tomography array and the TDSI algorithm in other research problems was discussed.

ACKNOWLEDGMENTS

This material is based upon work supported in part by the U.S. Army Research Laboratory and Army Research Office under contract/grant number W911NF1010415.

REFERENCES

1. Ostashev, V. E., S. N. Vecherin, D. K. Wilson, A. Ziemann, G. H. Goedecke, 2009: Recent progress in acoustic travel-time tomography of the atmospheric surface layer, *Meteorol. Zeitschrift,* **18**, 125-133.

2. Wilson, D. K., D. W. Thomson, 1994: Acoustic tomographic monitoring of the atmospheric surface layer, *J. Atmos. Ocean. Tech.,* **11**, 751-769.

3. Raabe, A., K. Arnold, A. Ziemann, M. Schröter, S. Raasch, J. Bange, P. Zittel, Th. Spiess, Th. Foken, M. Göckede, F. Beyrich, J-P Leps, 2005: STINHO - STructure of turbulent transport under INHOmogeneous conditions - the micro-α scale field experiment and LES modeling, *Meteorol. Z.,* **14**, 315-327.

4. Seliger, M., M. Barth, A. Raabe, 2005: *Akustische Lauzeittomographie in Ilmenauer Fass* (Technical Report, Leipzig Institute of Meteorology, Leipzig).

5. Ostashev, V. E., A. Bedard, S. N. Vecherin, D. K. Wilson, 2009: Acoustic travel-time tomography of the atmospheric surface layer, *ASME Intern. Mech. Eng. Congress on Sound Propagation in the Atmosphere* (Lake Buena Vista, Florida).

6. Vecherin, S. N., V. E. Ostashev, G. H. Goedecke, D. K. Wilson, A. G. Voronovich, 2006: Time-dependent stochastic inversion in acoustic travel-time tomography of the atmosphere, *J. Acoust. Soc. Am.*, **119**, 2579-2588.

7. Vecherin, S. N., V. E. Ostashev, A. Ziemann, D. K. Wilson, K. Arnold, M. Barth, 2007: Tomographic reconstruction of atmospheric turbulence with the use of time-dependent stochastic inversion, *J. Acoust. Soc. Am.,* **122**, 1416-1425.

8. Vecherin, S. N., V. E. Ostashev, D. K. Wilson, A. Ziemann, 2008: Time-dependent stochastic inversion in acoustic tomography of the atmosphere with reciprocal transmission, *Meas. Sci. Technol.*, **19**.

9. Vecherin, S. N., V. E. Ostashev, D. K. Wilson: Assessment of the time delays in acoustic travel-time tomography of the atmosphere, *J. Acoust. Soc. Am.* (to be submitted).

10. Ostashev, V. E., S. N. Vecherin, D. K. Wilson, C. Fairall, 2011: Recent developments in acoustic tomography of the atmosphere, *14th Intern. Symp. on Long Range Sound Propagation* (Annapolis, MD).

11. Vecherin, S. N., V. E. Ostashev, D. K. Wilson, A. Grachev, 2012: Utilization of an acoustic tomography array as a large sonic anemometer/thermometer, *Proceedings of Meetings on Acoustics*, **14**, 045003.